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Measurements of temperature on LHC thermal models

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Abstract

Full-scale thermal models for the Large Hadron Collider (LHC) accelerator cryogenic system have been studied at CERN and at Fermilab. Thermal measurements based on two different models permitted us to evaluate the performance of the LHC dipole cryostats as well as to validate the LHC Interaction Region (IR) inner triplet cooling scheme. The experimental procedures made use of temperature sensors supplied by industry and assembled on specially designed supports. The described thermal models took the advantage of advances in cryogenic thermometry which will be implemented in the future LHC accelerator to meet the strict requirements of the LHC for precision, accuracy, reliability, and ease-of-use. The sensors used in the temperature measurement of the superfluid (He II) systems are the primary focus of this paper, although some aspects of the LHC control system and signal conditioning are also reviewed. © 2001 Published by Elsevier Science Ltd.

Keywords: Temperature sensors; He II systems; Heat exchangers; Cryostats

1. Introduction

The Large Hadron Collider (LHC), now under construction at CERN, will produce two counter-rotating proton beams, each with an energy of 7 TeV for head on collisions at 4 points. The 27-km circumference of the LHC lattice is composed of a succession of insertions and arcs. The eight arcs are mainly composed of dipoles and quadrupoles and eight inner triplets are part of the Interaction Regions (IRs). NbTi superconducting magnet windings are surrounded by pressurized superfluid helium (He II) in order to improve their current-carrying capacity and provide a 8.4 T magnetic field. The heat load generated by these magnets must be extracted in order to keep the magnets superconducting. This heat load is transported by conduction in stagnant and pressurized He II to a heat exchanger tube where it is carried away by a flow of saturated two-phase superfluid helium.

Cryogenic performance tests were required and carried out in order to validate the LHC IR inner triplet cooling scheme. This validation was accomplished by measuring the performance of the external heat exchanger tube using a thermal model designated as the Inner Triplet Heat Exchanger Test Unit (IT-HXTU) [1,2]. Prior to this project, a similar approach was used at CERN to measure the thermal performance of the LHC arc dipole cryostats, with the Cryostat Thermal Model (CTM) [3,4].

Both thermal models made use of hundreds of temperature sensors, pressure transducers, liquid level gauges, control valves, mass-flowmeters and heaters. This instrumentation, its signal conditioning and control system provided data for determining a 3-D analysis of the thermal and hydraulic behavior of the He II systems in the inner triplet and for measuring the performance of the LHC arc dipole cryostat. The large numbers of temperature sensors used are Resistive Temperature Detector (RTD) types. The temperature sensors were immersed in the He II or installed under vacuum conditions on LHC prototype components. These cryogenic thermometers have commercial sensors assembled on supports especially designed to satisfy the strict LHC requirements [5,6]. Assembly and calibration of the sensors in their support were performed at Fermilab and at CERN. A description of the thermal models, the type of temperature sensors used, their installation, their signal conditioning, their control system and their calibration techniques are reviewed below.

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2. The LHC thermal models

2.1. Inner Triplet Heat Exchanger Test Unit (IT-HXTU)

The inner triplet is a set of three cryostats containing four quadrupole magnets that focus (or defocus) the colliding beams causing the collisions. Two inner triplets bracket each of the four interaction points of the LHC. In these regions beam-induced heating is of great concern. We estimated that beam-induced heating produces a 184 W dynamic heat load to be extracted at 1.9 K in addition to the 18 W static heat load over these 30-m regions. This 202 W load should be compared with ~40 W heat load typical of the 107-m arc cell. The cooling scheme of the inner triplet is based on heat exchange between the stagnant and pressurized He II surrounding the magnets and the saturated two-phase He II flowing in a heat exchanger tube. To extract the large heat load of the IR, a 97.5-mm outer diameter corrugated copper heat exchanger tube is used. Due to the tube diameter it can only be located outside of and parallel to the cold mass, which houses the magnet.

The IT-HXTU was a 30-m long cryostat containing full cryogenic instrumentation and an arrangement of pipes including resistive heaters, which simulated the magnets and dynamic heat loads. The IT-HXTU was designed with the full 800-l volume of pressurized He II of the inner triplet. The test unit was composed of a feed box, four-coupled cryostat modules and a turnaround box. Pressurized He II filled the volume of the magnet simulator pipes, the pipes surrounding the heat exchanger tube and their connecting pipes. Fig. 1 shows a simplified schematic of the test facility with the pressurized He II bath, the saturated He II circuit, the Joule–Thomson (JT) valve and the resistive heaters. The heat exchanger tube, the magnet simulator pipe and the connecting pipes are shown as well as the location of four of the temperature sensors (T1, T2, T3 and T4) and a pressure transducer (PT). This unit was designed at Fermilab and built by US industry as part of the US LHC Accelerator Collaboration program to develop the LHC IR quadrupole system. It was fully automated and tested at CERN.

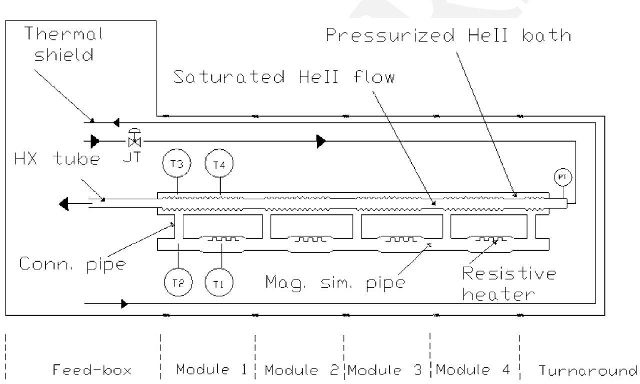

Fig. 1. IT-HXTU simplified schematic. The pressurized He II bath, the saturated He II circuit, the Joule–Thomson (JT) valve, the resistive heaters, the heat exchanger tube, the magnet simulator pipe and the connecting pipes are shown as well as the location of four of the temperature sensors (T1, T2, T3 and T4) and a pressure transducer (PT).

The main purpose of this study was to validate the inner triplet cooling scheme by checking the temperature rise in the stagnant and pressurized He II due to static and dynamic heat loads. Another purpose of the IT-HXTU study was to investigate the cryogenics process control of the LHC 1.8 K cryogenic loop to be implemented in the future LHC accelerator.

2.2. Cryostat Thermal Model (CTM)

The arc cold mass is mainly composed of a superconducting magnet threaded by a 53.4-mm inner diameter smooth heat exchanger copper tube. It operates at about 1.9 K. The static load coming from the ambient dominates the total heat load to be extracted at 1.9 K. The cryostat system intercepts the static heat load and insulates the cold mass from heat radiated and conducted from the environment over the eight 2.5-km long arcs.

The original CTM was developed at CERN using a 10-m long prototype dipole cryostat and was used to measure the thermal performance of the LHC arc dipole cryostat. As for the IT-HXTU, the CTM was composed of a feed-box, a cryostat unit and a turnaround box. No magnets were used in the CTM. A low-mass double-walled stainless steel cylindrical structure simulated the cold mass surface and temperature. This dummy cold mass was spot-welded and gave the appropriate hydraulic cross-section. Two concentric aluminum thermal screens were actively cooled at 5–10 and 50–75 K, respectively. These screens were wrapped with Multi-Layer Insulation (MLI) and shield the dummy cold mass.The LHC thermal load conditions were simulated with heat loads generated by Joule-effect through electrical resistances installed on the dummy cold mass and thermal screens surfaces.

The CTM provided precise measurements of heat deposited at different temperature levels (1.9, 5–10, 50–75 K). One of the main issues of the CTM version 3 was to investigate the efficiency of an actively cooled thermal screen at 5–10 K and to compare the influence of different MLI system configurations.

3. Types of temperature measurement

3.1. IT-HXTU measurements

We mainly measured the temperature distribution in the He II system and the small temperature differences between the pressurized and the saturated He II, $T - T_{sat}$. While simulating the LHC thermal conditions, these measurements permitted us to analyze the heat transfer though pressurized He II as well as the Kapitza resistance at the interface between the corrugated copper tube and the liquid. The small temperature differences required very precise and accurate measurements.

RTDs like Cernox™ RTDs, Allen-Bradley® sensors and Platinum RTDs were used. The four-wire technique was used in order to precisely measure temperatures. Cernox™ RTDs were mounted to 35 mm × 11 mm × 1.6 mm Printed Circuit Board (PCB) cards. The Cernox™ RTD was suspended in a machined hole in the PCB card by 0.79-mm outer diameter insulated wires and GE-7031 varnish. The two original sensor leads were trimmed and soldered to gold plated copper slide contacts. Fig. 2 is a photograph of a Cernox™ RTD installed on a PCB card. The large holes were used for installation into the process piping and the small ones were used for the insulated wires. The mechanical and thermal contact between the sensor and the card was thereby reduced. The ease-of-use of this composition simplified the sensor calibration, handling and installation procedures, therefore it permitted us to reduce the extrinsic stresses applied to the sensor. The effect of the intrinsic stresses was reduced by cold shocking the composition in liquid nitrogen and warmed up to room temperature 10 times before they were installed for calibration. The complete cards were anchored to support systems inside IT-HXTU pipes. Four low thermal conductivity manganin wires were soldered to the two cardcontacts. These instrumentation wires were routed through a long stainless tube to a sealed connector at room temperature. The diameter of the instrumentation stainless steel tubes was selected to reduce the heat transported by conduction in pressurized He II.

About 54 Cernox™ RTDs were implemented on their PCB cards and were immersed in the pressurized He II bath along the pipes surrounding the heat exchanger tube, others close to the connecting pipes and some in the magnet simulator pipes.

In addition, the saturated He II flow temperatures were inferred from saturated pressure measurements. Since the pressure in the heat exchanger tube was subatmospheric, the risk of air leaks through the different instrumentation feedthroughs was avoided by using room temperature pressure transducers and liquid level gauges. Indeed, any direct temperature measurements would lead to the possibility of leaks.

In order to illustrate the order of magnitude of the temperatures measured, Fig. 3 shows the temperature difference, $T - T_{sat}$, between the pressurized temperature and the saturated temperature fixed at 1.85 K, for different heat loads. The behaviors of thermal gradients are plotted for four sensors installed along the heat flow pattern in the pressurized He II (see Fig. 1). T1 and T2 were measured in the magnet simulator pipe, in the proximity of the resistive heater and close to the connecting pipe, respectively. T3 and T4 were measured in the pipe surrounding the heat exchanger tube, close to the connecting pipe and in the middle of the module,

Fig. 2. View of a Cernox™ RTD installed on the IT-HXTU Printed Circuit Board card. The card size is 35 mm × 11 mm × 1.6 mm.

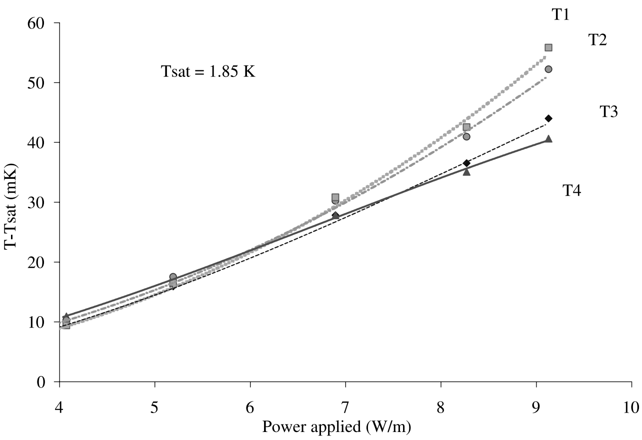

Fig. 3. Temperature differences evolutions, $T - T_{sat}$, between the pressurized temperature and the saturated temperature fixed at 1.85 K, for different heat loads applied to resistive heaters. T1 and T2 were measured in the magnet simulator pipe, in the proximity of the resistive heater and close to the connecting pipe, respectively. T3 and T4 were measured in the pipe surrounding the heat exchanger tube, close to the connecting pipe and in the middle of the module, respectively.

respectively. The pressure transducer, PT, permitted us to determine the saturated He II temperature. The pressurized He II temperature, T, rose from the heat exchanger tube to the resistive heater proximity. Up to 55 mK of temperature difference with the saturated He II was measured in the proximity of the magnet simulator electrical resistance when a load equivalent to 9 W/m was applied.

3.2. Temperature measurements under vacuum

111 temperature sensors and other instrumentation devices were implemented on the CTM. Although two Cernox™ RTDs were immersed in the pressurized He II bath, thermal measurements performed under vacuum conditions were preferred for the CTM. These two immersed sensors determined the correlation of the temperature measurement performed under vacuum, with the temperature of the cryogen. As part of the thermal measurement, the cold mass temperature was measured with sensors especially installed on the cold mass skin under vacuum conditions. In order to meet the LHC thermal requirements and equip the future accelerator, CERN developed a special technique of temperature measurement under vacuum. The CTM was also an opportunity to further validate the use of the vacuum and cryogenic thermometers.

The alternative to measure temperature in the insulation vacuum permitted us to avoid the use of cold vacuum-tight electrical feedthroughs. Therefore, the temperature of the solid wall in contact with the cryogen was what was measured rather than the cryogen temperature. Since thermal contact and heat transfer is an essential issue not satisfactorily tackled in the past, CERN developed cryogenic vacuum thermometer kits with three heat-sink blocks and serpentine leads in PCB cards [5]. Fig. 4 shows the layout of the resulting vacuum and cryogenic thermometer. These serpentine leads are equivalent to a 670-mm long and 32-μm diameter copper wire, and are fabricated using PCB techniques. A commercial sensor is inserted in the temperature sensor cavity of the PCB card. The card is divided into three zones to improve the heat-sinking due to conduction through the wires to the mounting surface.

Thermal measurements performed under vacuum conditions were done through thermal impedance across the cryostat wall, thus it was mandatory to provide the thermometer with a efficient thermal anchoring. Vacuum grease and indium helped to reduce the thermal impedance. CERN developed accessories for a better implementation of the industrial-type vacuum cryogenic

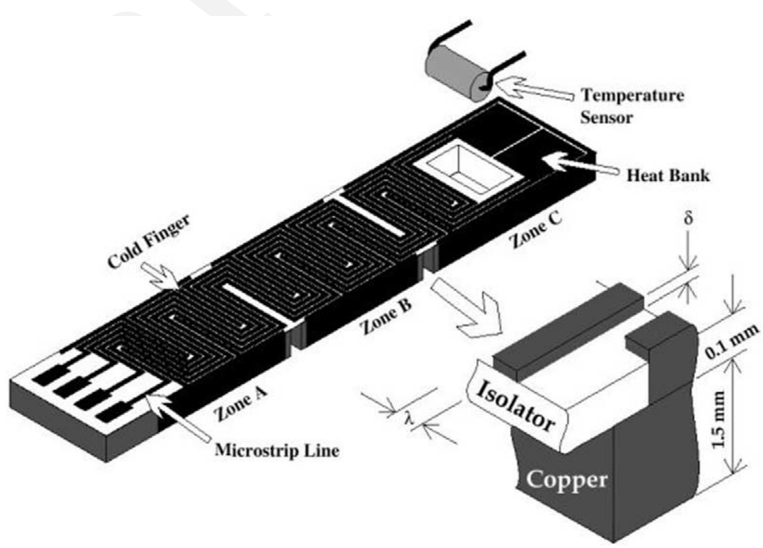

Fig. 4. CERN cryogenic thermometer layout showing the meandering microstrip lines of width λ and thickness δ, the solid copper plate thickness corresponds to that of a standard Allen-Bradley® sensor. The thermometer size is 100 mm × 10 mm × 2 mm.

thermometers. Three copper blocs were brazed to the mounting surface and used as heat sinks in order to improve the thermal contact between the vacuum cryogenic thermometer and the surface. The thermometer was screwed to the flat copper blocks surfaces. Compatible copper blocks and protection cap ensured an isothermal substrate of the body and a thermal radiation protection, respectively.

About 55 commercial Cernox™ RTDs and Allen-Bradley® sensors were inserted into the vacuum cryogenic thermometer kits and mounted on copper blocks that were brazed on the dummy cold mass skin or on the helium plumbing.

4. Sensor calibration

Due to the large number of calibrations RTDs required by HEP accelerators like the Tevatron, the SSC and the LHC, on site calibration stations were developed at Fermilab and CERN.

To satisfy this large demand, Fermilab up-dated its calibration station to calibrate 96 RTDs in two different circuits at the same time. The reference temperature is given with a glass-carbon sensor, the accuracy of which is regularly checked against the vapor pressure of He^4.

An innovative calibration test bench was developed at CERN in order to supply the LHC with thermometers measuring in the vacuum condition [7]. This calibration station is well adapted to the large-series production required for the LHC. The temperature standards are maintained and are retraceable to the Italian meteorological institute. Their sample to sample reproducibility is 2 mK in the 1.5–300 K temperature range.

The calibration data are processed either on or off-line to reject outliers and afterwards produce a suitable mathematical approximation. Mathematical approximations for Allen-Bradley® and Germanium sensors have been well documented elsewhere [8]. For Cernox™ RTDs several functions can be used, for instance Fermilab and Lakeshore® use Chebychev polynomials, CERN uses logarithmic polynomials and several metrologists use splines. For certain equipment it is more convenient to use piecewise linear interpolations, the number of interpolating points depends on the calibration points and the required accuracy.

The IT-HXTU temperatures were converted from resistances via calibration fits implemented in the Programmable Logic Controller (PLC) or available from the acquisition program.

5. Control system and conditioner

The thermal measurement analysis needs to consider the process used to power the cryogenic thermometers. The signal conditioning for the cryogenic thermometry in the IT-HXTU was similar to the one foreseen for the LHC and is detailed elsewhere [9]. The signal conditioner supplied a given excitation current over a pair of wires and it read the voltage developed across the sensor resistance over a second pair of wires. The Cernox™ RTDs used for the IT-HXTU had a very wide resistance span and for this reason CERN developed a linear multi-range signal conditioner.

Industrial control equipment (12-bit Analog-to-Digital Converters) digitized, the read signal to be used by computerized control or diagnostics. After the voltage was amplified and corrected the read signal was sent to the analog process controller. The temperatures were determined by a linear interpolation routine running on the PLC. The process automation was based on a PLC. Six closed control loops, alarms and interlocks were implemented through the PLC. PLC parameterization was available with an Engineering Work Station (EWS). An Operator Work Station (OWS) ran PCVuew32®, it permitted the data storage and the process supervision.

Linear and for the first time Non-Linear Predictive Controllers (NLPC) [10,11] had been developed and tested in the IT-HXTU. Fig. 5 shows how temperature measurements can be used to control the JT valve. These controllers were better able to tackle non-linearities (e.g. dead-time, inverse response, temperature dependence of physical parameters, etc.) than the standard Proportional, Integral and Derivative (PID) algorithm.

6. Reliability of LHC temperature measurements

The tests of both thermal models depended on accurate and reliable temperature measurements. High accuracy temperature measurements at temperatures below 50 K are difficult because on one hand most commercially available thermometers require individual

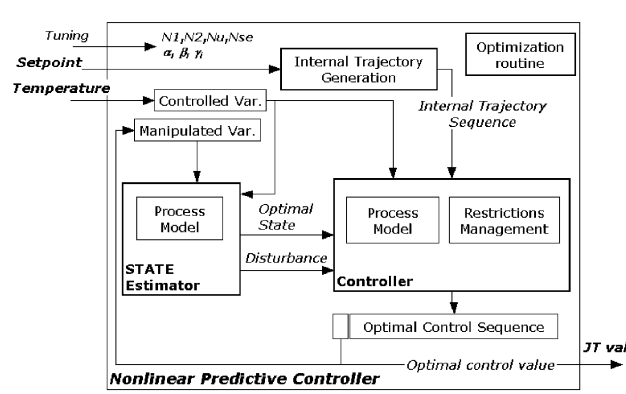

Fig. 5. Non-Linear Predictive Controller (NLPC) system.

calibrations and on the other hand the thermometer characteristics depend on the environment. Sources of uncertainty for a temperature measurement are the absolute uncertainty, reproducibility of temperature standards used for calibration, effects of Joule self-heating for electrical thermometers, thermal coupling with the body under investigation, etc.

6.1. Characteristics

The sensors mounted on their PCB were defined by the following characteristics.

The resistance change per unit temperature ($S = \mathrm{d}R/\mathrm{d}T$) defines the sensitivity of the RTD type thermometers. Whereas Platinum RTDs are approximately linear transducers above 77 K (constant conductivity), Cernox$^{\mathrm{TM}}$ RTDs and Allen-Bradley® sensors sensitivity depends on the temperature. The Cernox™ RTDs used in the LHC thermal models have a sensitivity of the order of 2×10^4 Ω/K at 1.9 K. For comparison, Platinum RTDs sensitivity is 0.4 Ω/K at 77 K. For calibrated Cernox™ RTDs used in the thermal models, the fractional resolution was of the order of 0.25% for temperature below 10 K. The stability of these sensors was on the order of ± 3 mK at liquid helium temperature. Cernox™ RTD, like Allen-Bradley® are sensitive to thermo-cycles. Their reproducibility, sample to sample, was of the order of 10 mK at 1.8 K.

As part of the measuring process sequence, the signal conditioning uncertainty also qualified the thermal measurement. Both sensors and signal conditioning had to share evenly the accuracy budgeted. The signal conditioning accuracy for the IT-HXTU Cernox™ RTDs was 3.3×10^{-3} for temperatures below 6 K. The maximum error due to the electronic processing was estimated to 0.2% of the temperature measured and permitted us to use an absolute accuracy of 10 mK below 2.2 K.

All together, the sensor, its calibration, fit and signal conditioning provided temperature measurement with an error of ± 5 mK at 1.8 K.

6.2. Self-heating effect

Apart from the problems of thermometer stability, we needed to determine the current limit due to self-heating. The heat generated by Joule-effect in the lead wires can affect the measurements. This heat will create a temperature variation, $T - T_0$, of the nominal value, T_0. T_0 is the reference temperature measured with a very lower excitation current preventing the self-heating effect. This effect can be corrected with a model implemented in the measurement. Subtraction of the temperature variation calculated by mathematical approximation for the cycle under investigation can be performed.

Since the calibration of the Cernox™ RTD showed resistances as high as 56 kΩ at 1.6 K and 90 kΩ at 1.4 K, we decided to quantify the influence of the overheating and self-heating for the IT-HXTU thermometers. A second reason to perform this test was to check the influence of the current excitation. Indeed, the excitation current supplied to the Cernox™ RTDs during the IT-HXTU test run was five times higher than the one used during their calibration. This test allowed us to correlate the temperature variation and the excitation current for several reference temperatures and several sensor resistances. We used nine temperature sensors, with resistances that vary from 20 to 60 kΩ at 1.6 K. For each sensor the reference temperature, T_0, was calculated from its individual Chebychev polynomial function, generated by fitting the initial calibration points obtained with a 0.2 μA current source. The overheated temperature, T, was given by applying the resistances measured for various currents to the Chebychev polynomial function. The temperature variation was therefore the difference between the overheated value and the reference value. Fig. 6 shows the temperature variation, $T - T_0$, vs. applied currents (0.5, 1, 2, 5 and 10 μA) for various temperature references, T_0 (1.4–3.2 K). As expected, the measurements show larger variation at lower temperatures. For example, a 5 μA excitation current generates a temperature variation of the order of 70 mK for a reference temperature of 1.6 K (4.4% of the nominal value), whereas this variation drops to 3.3 mK if the excitation current is 1 μA.

As a conclusion to this test, the use of the high resistance temperature sensors without further correction

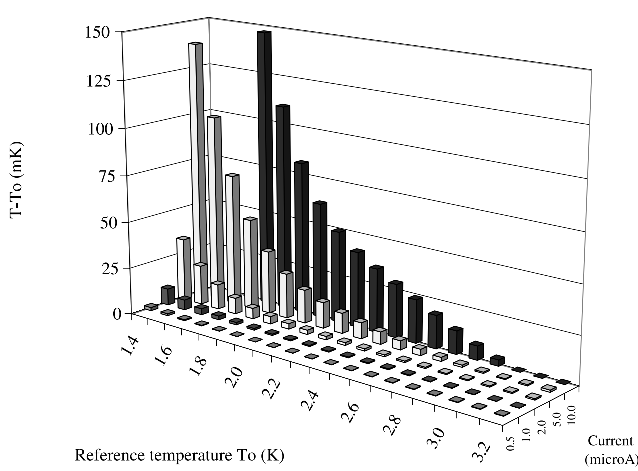

Fig. 6. Temperatures variation, $T - T_0$, of a Cernox™ RTD vs. applied currents (0.5, 1, 2, 5 and 10 μA) for various temperature references, T_0 (1.4–3.2 K). The sensor resistance measured for a reference temperature of 1.8 K and with a 0.2 μA excitation current is equal to 39 kΩ. Temperatures variations measured with an excitation current of 10 μA and for temperatures lower than 1.7 K are not showed in order to focus on the temperature range of interest for the LHC thermal models.

has been validated, since no significant error was measured for excitation current equivalent to the one used during the IT-HXTU test run.

6.3. Evaluation of uncertainties in the LHC environment

The heat load transmitted by conduction through the instrumentation wire to the system induced a systematic error in the measurement of the temperature. The heat load by conduction though wires was estimated to be 4×10^{-14} W per sensor for the CTM. The CTM wires were routed in the insulation vacuum and thermalized with dedicated PCB foils at several temperature levels. This heat load was on the order of 5×10^{-11} W for the IT-HXTU, where instrumentation wires were routed from the 1.9 K bath to the connector at room temperature.

A major source of error can be the quality of vacuum that produces a heat flow through the vessel/pipe walls thus resulting in a temperature gradient across the wall [3,12]. For a degraded vacuum (higher than 10^{-3} Pa), we observe a non-negligible temperature gradient across the wall separating the cryogen from the sensor. The temperature gradient increase due to degraded vacuum will depend on the wall material (typically stainless steel) and on the operating temperature because thermal parameters have a very strong dependence on temperature.

Contact between the cryogen and the pipe wall may not be sufficiently good in order to obtain a pipe outer wall with a temperature sufficiently close with the one of the fluid. In such case provisions for a heat exchanger were required if a proper non-invasive temperature measurement was desired.

When using CERN's vacuum cryogenic thermometers, the calibrations are performed in the same conditions as those expected in the field. This is possible because the temperature sensor attachment is not modified during installation and even Joule self-heating effects can be reproduced with relatively good accuracy. For instance when measuring superconducting dipoles an accuracy better than 0.01 K was obtained in spite of the fact that the sensor Joule self-heating was of the order of 0.10 K. In order to obtain such performance the only installation constraint is to provide a flat and smooth surface to screw the thermometers. The thermal contact is further improved by using contact grease Apiezon® N. This assembly technique was considered with the CTM, where a set of three copper blocs were brazed to the mounting surfaces.

Temperature sensor thermo-cycling or mounting technique may produce stress on the sensitive material, which imply changes in the sensor calibration. The Fermilab technique of having them processed and stress-free mounted on PCB cards improves the quality of the measurement. The long-term stability of RTDs submitted to cryogenic thermal cycling was investigated at Fermilab and at CERN [13]. This study shows that sensors made specifically for cryogenic applications have a better reproducibility in their characteristics. Cernox™ RTDs were improving their characteristics after exposed to 25 thermal cycles. Above 20 K, Allen-Bradley® sensors are also more sensitive to thermo-cycle than Cernox™ RTDs. Each sensor used on thermal models had been previously thermo-cycled before being calibrated. However it should be noted that commercial temperature sensors are often cycled and in the future the necessity of further cycling may not be necessary.

Within the accelerator hardware, cryogenic instrumentation has to be insensitive to neutron irradiation and sometimes to high magnetic field. Hence, the laboratories have investigated the influence of these environmental effects on commercial sensors. Neutron irradiation tests of LHC vacuum cryogenic thermometers in superfluid helium were performed at CERN [14]. In addition, stability of sensors in high field magnets has been frequently addressed [15]. Industry searches and provides the laboratories with sensors based on material with the smallest magneto-resistance resulting in sensors with least orientation dependence at low temperature. For instance, Germanium sensors are very sensitive and accurate at He II temperature but they could not be used in a magnetic field.

Both LHC thermal model tests took advantage of advances in cryogenic thermometry, although magnet and proton beam were not used.

7. Conclusion

Reliable and ease-of-use cryogenic thermometers permitted us to measure the LHC thermal models performances. The stability of the Cernox RTDs was estimated to ±3 mK and the sample to sample reproducibility is 2 mK. He II temperature systems were measured with an error of ±5 mK. These thermal measurements lead to an understanding of the behavior of the LHC He II systems. As a consequence, the cryostat design was optimized and the LHC IR inner triplet cooling scheme was validated as well as the first NLPC. Thermometry capabilities have been developed at CERN and at Fermilab in order to meet the stringent requirements on the temperature control of the LHC magnets.

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